

Salty Water Cerenkov Detectors for Solar Neutrinos

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Abstract

The addition of certain solutes to a water Cerenkov detector will introduce new charge-current channels for the detection of ν_e s. The experimental conditions necessary to exploit such signals - large volumes and very low backgrounds - should be reached for the first time in SuperKamiokande and SNO. I compare some of the more attractive possibilities (^7Li , ^{11}B , ^{35}Cl) in terms of counting rate, reliability of the cross section, specificity of signal, and potential for distinguishing competing solutions to the solar neutrino puzzle.

The purpose of this letter is to stimulate discussions of additional uses of water Cerenkov detectors in solar neutrino physics. The introduction of relatively inexpensive solutes can produce new charge-current signals that can be combined with $\nu_x - e$ elastic scattering to determine the spectra of both electron and heavy-flavor neutrinos. The advances being made by SuperKamiokande [1] and the Sudbury Neutrino Observatory (SNO) [2] - extraordinary fiducial volumes and radiopurities - are essential to such schemes. The discussion below of three possible solutes will illustrate what can be achieved in terms of counting rates, specificity of the signal, and reliability of cross section - as well as the kinds of compromises that experimenters must consider when attempting to exploit such signals in solar neutrino experiments.

Some of the advantages of deuterium, the neutrino target in SNO, are also offered by the series of light “n - p” systems, those stable mirror nuclei with $T = 1/2$. Quite often the cross sections can be determined very accurately. For light targets (e.g., ${}^7\text{Li}$ and ${}^{11}\text{B}$), the thresholds are quite low, so that rates, especially per target nucleon, are very large. Alternatively, in the heaviest cases (e.g., ${}^{31}\text{P}$, ${}^{35}\text{Cl}$, and ${}^{39}\text{K}$), the Coulomb interaction has produced thresholds for (ν_e, e^-) that are sufficiently high that the subsequent β^+ decay of the daughter nucleus might be observable, providing a distinctive coincidence in time and position.

In terms of counting rate and reliability of cross section calculations, the outstanding example among the light mirror systems is ${}^7\text{Li}(\nu_e, e^-){}^7\text{Be}$. Only two transitions are significant, the mixed Fermi (F) - Gamow Teller (GT) analog transition to the ${}^7\text{Be}$ ground state ($E_\nu^{thresh} = 0.861$ MeV) and the GT transition of superallowed strength to the 0.478 MeV first excited state ($E_\nu^{thresh} = 1.339$ MeV). The allowed matrix elements (Table 1) can be extracted from the electron capture rates for ${}^7\text{Be}$. Thus the cross section for a normalized ${}^8\text{B}$ neutrino spectrum is known to about 1%, $\sigma({}^8\text{B}) = 3.50 \cdot 10^{-42}$ cm². Because of the low threshold and the concentration of the transition strength near threshold, properties ${}^7\text{Li}$ shares with deuterium, the electron spectrum is particularly sensitive to distortions in the incident neutrino spectrum. I will return to this issue later.

A number of lithium-bearing solutes could be considered, several of which (e.g., LiCl) are very soluble. For definiteness I will consider a 5% solution of LiOH, a modestly soluble compound (12.8 g/100 cc at 20°C) containing no other principal isotopes that interact with solar ν_e s. For the 22 kiloton fiducial volume of SuperKamiokande and an undistorted ^8B ν_e flux consistent with the results [3] of Kamioka II/III ($3 \cdot 10^6/\text{cm}^2 \text{ sec}$, or about half the standard solar model [4] (SSM) result), the total event rate is 8480/year, comparable to the ν_x -electron inelastic scattering rate. For a threshold trigger on the apparent electron energy of $E_A > 5 \text{ MeV}$ and a Gaussian resolution function [1] of $\sigma(E) = 0.16E \sqrt{\frac{10\text{MeV}}{E}}$, 87.4% of these events would be detected.

In the early planning stages of SUNLAB [5] a concentrated ($\gtrsim 30\%$) solution of LiCl was investigated but this option was abandoned because of the associated severe light attenuation, especially in the UV. A naive extrapolation of the measurements suggests this problem would not arise for the much lower concentrations considered here. That is, the large volume of SuperKamiokande makes a Li solute feasible. The absence of an attenuation problem at low concentrations must be established experimentally, of course.

There is one unfortunate aspect of ^7Li : the F and GT angular distributions, proportional to $1 + \hat{\nu} \cdot \vec{\beta}_e$ and $1 - \frac{1}{3}\hat{\nu} \cdot \vec{\beta}_e$, respectively, conspire to produce a nearly isotropic cross section for ^8B neutrinos

$$\sigma \propto (1 + \alpha(E_e)\hat{\nu} \cdot \vec{\beta}_e) \quad (1)$$

where $\hat{\nu}$ is the unit vector in the direction of the neutrino, $\vec{\beta}_e = \vec{p}_e/E_e$, and $\alpha(E_e) \sim -0.02 \pm 0.02$ for $5 \text{ MeV} \lesssim E_e \lesssim 10 \text{ MeV}$. (The precise variation with E_e can be computed from the results in Table 1.) Thus, unlike $\nu_x - e$ elastic scattering, the angular distribution cannot be used to separate neutrino events from an isotropic background. This constrains useful measurements to those larger electron energies where background rates are negligible.

For this reason, one might consider other solutes where the angular distribution is more distinctive. Among the light mirror nuclei $^{11}\text{B}(\nu_e, e^-)^{11}\text{C}$, with a threshold of 1.982 MeV, is probably the best alternative to ^7Li . Boron was discussed previously as a solar neutrino

target in the proposal Borex [6], a predecessor to Borexino.

The nuclear physics is summarized in Table 1. The F-GT transition to the ^{11}C ground state carries 73% of the ^8B ν_e absorption strength. Thus the reaction is again reasonably hard. The transition strength is fixed by the ^{11}C lifetime. The first excited state accounts for 16% of the cross section. Its strength is also tightly constrained by experiment, as the γ -decay rate from this state to the ground state is known in both ^{11}B and ^{11}C . This allows one to extract

$$|\langle J_f || \sum_{i=1}^A (\mu_1 \vec{\sigma}(i) + \vec{\ell}(i)) \tau_3(i) || J_i \rangle| \quad (2)$$

where $\mu_1 = 4.706$. The large isovector magnetic moment means Eq. (2) is dominated by the GT contribution, which can be extracted by doing a shell model calculation of the matrix element ratio $\eta = \langle \ell(i) \tau_3(i) \rangle / \langle \mu_1 \vec{\sigma}(i) \tau_3(i) \rangle$. Since η is small (-0.144 in a 1p-shell calculation [7]), the nuclear structure uncertainties in this extraction are quite modest. The result (Table 1) is consistent with direct shell model estimates of the GT matrix element, corresponding to an effective $F_A^{eff} = 0.94$ near the expected value.

Essentially all of the remaining 10% of the cross section is carried by the $5/2^-$ (4.32 MeV) and $3/2^-$ (4.80 MeV) second and third excited states in ^{11}C . The GT strengths in Table 1 are shell model [7] results: calculations analogous to that described above cannot be made because the γ -decay lifetimes in ^{11}C have not been measured. If they were, and if we assign a pessimistic error to shell model estimates of η of $\pm 50\%$, the uncertainty in the total cross section $\sigma(^8\text{B}) = 1.41 \cdot 10^{-42} \text{ cm}^2$ could be reduced to less than $\pm 5\%$. Thus ^{11}B is another case where nuclear structure uncertainties are under reasonably good control.

A possible solute is the weak acid H_3BO_3 , with a solubility of 6.35 g/100 cc at 20°C . Assuming a 5% solution, the 22 kiloton fiducial volume of SuperKamiokande, and an undistorted ^8B ν_e flux of $3 \cdot 10^6 / \text{cm}^2 \text{ sec}$, the total event rate is 1430/year. For the SuperKamiokande threshold trigger $E_A = 5 \text{ MeV}$ and resolution function, 60% of these events would be detected.

The angular distribution is again precisely calculable using the results of Table 1. An

approximation to this result, in the notation of Eq. (1), is

$$\alpha(E_e) = 0.31 + 0.063 (E_e - 7.5) \quad (3)$$

where E_e is in MeV. The cross section is modestly forward peaked, with $\sigma(0^\circ)/\sigma(180^\circ) \sim 1.9$ at $E_e = 7.5$ MeV. As in the case of $\nu_x - e$ scattering, this angular dependence can be exploited to distinguish an important fraction of neutrino events from the isotopic background. However this more specific signal comes at a price: the event rate, relative to ${}^7\text{Li}$, is significantly lower, and the higher threshold (by 1.1 MeV) somewhat restricts the range of neutrino energies that can be sampled.

A very different experimental strategy is possible with heavy mirror systems. Because the introduction of ${}^{40}\text{K}$ in a water Cerenkov detector would be inadvisable, the best case may be

$$\nu_e + {}^{35}\text{Cl} \rightarrow e^- + {}^{35}\text{Ar} \quad (4a)$$

$${}^{35}\text{Ar} \rightarrow {}^{35}\text{Cl} + e^+ + \nu_e, \tau_{1/2} = 1.775 \text{ sec} \quad (4b)$$

where the maximum positron energy is 5.454 MeV. The large threshold produces a potentially distinctive neutrino reaction signal: a prompt electron followed by a positron correlated in time (~ 1.775 sec delay) and position. The time distribution must follow the ${}^{35}\text{Ar}$ decay curve. Furthermore, there is very significant peaking of the prompt electrons in the forward direction because the F strength dominates the analog transition: $\alpha(E_e) \sim 0.86$ in Eq. (1). All of these considerations conspire to make the signal unusually clean.

The cross section can be determined precisely from the ${}^{35}\text{Ar}$ β decay lifetime and measured decay branches. The superallowed ground state transition accounts for 94% of the transition strength. The remaining 6%, according to standard 2sld shell model calculations [8], is carried by transitions calibrated by ${}^{35}\text{Ar}$ β decay. Detailed results are given in Table 1. The substantial threshold leads to a cross section $\sigma({}^8B) = 2.23 \cdot 10^{-43} \text{ cm}^2$, considerably smaller than those in ${}^{11}\text{B}$ and ${}^7\text{Li}$.

While a number of highly soluble Cl salts might be used, NH_4Cl is an attractive choice because it can be synthesized from very high purity gases [9]. A 10% solution would produce 400 events/year in a 22 kiloton volume, assuming a ^8B neutrino flux of $3 \cdot 10^6/\text{cm}^2 \text{ sec}$. Event detection is governed by the prompt trigger threshold (5 MeV) and the sensitivity to the delayed β^+ . The current Kamioka III data acquisition system is capable down to 1.6 MeV, with triggering efficiencies becoming sufficiently high ($\gtrsim 95\%$) by 2.5 MeV that the spectrum above this energy is undistorted [3,10]. Thus this is a reasonable threshold for the positron trigger. Folding these thresholds with the anticipated SuperKamiokande resolution yields efficiencies of 43.7% and 62.2% for the prompt electron and coincident positron, respectively. Thus the number of detected events from such a concentration of Cl in SuperKamiokande would be 109/year, comparable to the $\nu_x - e$ rate of Kamiokande III.

The key issue, whether such a modest signal will be swamped by accidental coincidences, was recently explored by members of the SuperKamiokande collaboration [10]. For the expected vertex resolution ($\pm 1\text{m}$ for low-energy events) and background rates (assuming the anticipated 250-fold decrease [10] in the radon content relative to Kamiokande III), the signal/accidental rate is ~ 1 . This is very satisfactory, given the angular and time distributions that will distinguish real events from background. As the rate of accidental coincidences depends quadratically on the radon concentration, it is clear that the substantially improved radiopurity of SuperKamiokande is essential to any such neutrino detection scheme.

The addition of one of the discussed solutes to SuperKamiokande will allow experimenters to compare electron and heavy-flavor neutrino signals as a function of energy. This is a capability not presently envisioned for either SuperKamiokande or SNO: the SNO neutral current signal, neutrons from the neutrino breakup of deuterium, measures an integrated rate. Neutral current sensitivity is provided by the $\nu_x - e$ reaction: the electron and heavy-flavor cross sections are in the approximate ratio 7:1. The comparison of the charge-current reaction off the solute to $\nu_x - e$ scattering would not be influenced by uncertainties in the electron detection efficiency.

To illustrate what might be learned, I have investigated four scenarios that would produce

identical ν_x - e rates under the operating conditions of Kamioka II/III: *i*) an undistorted ^8B flux reduced to about 50% of the SSM result ($3 \cdot 10^6/\text{cm}^2\text{sec}$); *ii*) the “small angle” Mikheyev-Smirnov-Wolfenstein (MSW) solution [11] for flavor oscillations ($\sin^2 2\theta = 0.005, \delta m^2 = 3.46 \cdot 10^{-6} \text{ eV}^2$); *iii*) the “large-angle” flavor oscillation solution ($\sin^2 2\theta = 0.825, \delta m^2 = 10^{-5} \text{ eV}^2$); and *iv*) the small-angle sterile oscillation solution ($\sin^2 2\theta = 0.005, \delta m^2 = 2.63 \cdot 10^{-6} \text{ eV}^2$). Figure 1 shows the event distribution, in 1 MeV bins, for the solute concentrations discussed earlier, a 3-year running time, and the envisioned experimental conditions for SuperKamiokande. Figure 2 shows the ratio of nuclear and ν_x - e event rates, normalized in each bin to the results for scenario *i*).

From Fig. 1a one sees that the ability of SuperKamiokande to distinguish between these scenarios using ν_x - e data depends heavily on the results from the lowest energy bins (below 7 MeV); that the effects are less than 10%, so that one must know the absolute efficiency of the detector at the few percent level; and that scenario *i*) cannot be distinguished from *iii*), nor *ii*) from *iv*) with any significant degree of confidence. The ^7Li results are quite interesting in this connection. Under the anticipated initial operating conditions [10] of SuperKamiokande, the signal/background rates in this channel will be approximately 3, 20, and 150 for events collected above 10, 11, and 12 MeV, respectively. The 3-year rates above these thresholds, 6680, 4095, and 2240 events for scenario *i*), respectively, are still quite reasonable. This reaction nicely complements ν_x - e scattering: the ratio of ^7Li to elastic scattering events (Fig. 2a) differs by more than 20% between scenarios *i*) and *iii*), and by about 17% between *ii*) and *iv*). These scenarios could be distinguished at confidence levels of approximately 8, 6, and 4σ , respectively, using the data above 10, 11, and 12 MeV (assuming negligible backgrounds in each case). These errors are dominated by the statistics for ν_x - e, which has the lower event rate in the highest energy bins.

The ratio of $^{11}\text{B}(\nu, e^-)^{11}\text{C}$ and ν_e - e events provides a similar constraint. The results shown in Fig. 2c were obtained by assuming that a portion of the ^{11}B events - those contributing to the angular variation in the cross section - could be separated from a larger, isotropic background in a maximum likelihood analysis. Including all events above the 5 MeV

SuperKamiokande threshold, the statistics are then sufficient to distinguish scenario *i*) from *iii*), or *ii*) from *iv*), at a confidence level of about 5σ . A similar calculation for the ratio of ^{35}Cl and ν_x - e scattering events (Fig. 2d) yields a confidence level of about 3σ , reflecting the limited ^{35}Cl event rate.

These calculations, while exploratory, demonstrate that certain low-cost solutes could significantly enhance the power of SuperKamiokande to test competing solutions of the solar neutrino puzzle. The case of ^7Li appears especially interesting due to its precisely known cross section and low threshold, which leads to large event rates for electron energies above 10 MeV, where SuperKamiokande backgrounds should be small. Hopefully the arguments presented here will stimulate experimenters to consider the technical issues associated with such solutes, including light attenuation, possible chemical effects on detector materials, solute-associated backgrounds, and background subtractions that might be made by varying solute concentrations or exploiting the earth's orbital variations.

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TABLES

TABLE I. Allowed nuclear matrix elements $|M|^2 = \text{BGT} + \text{BF}$ and the resulting cross sections, averaged over an undistorted ^8B neutrino flux.

Target	$E_f(\text{MeV})$	BGT	BF	$\sigma(^8\text{B})$ (10^{-42} cm^2)
^7Li	0.0	1.747	1.00	2.299 ¹⁾
	0.478	1.630		1.198 ¹⁾
	≥ 6.68			0.003 ²⁾
total				3.500
^6Li	0.0	2.580		0.057 ^{1),5)}
	≥ 1.67			0.002 ^{2),5)}
total				0.059 ⁵⁾
^{11}B	0.0	0.601	1.00	1.025 ¹⁾
	2.000	0.706		0.229 ³⁾
	4.319	0.681		0.079 ²⁾
	4.804	0.847		0.076 ²⁾
	≥ 8.1			0.003 ²⁾
total				1.412
$^{10}\text{B}(\text{total})$	≥ 3.35			0.009 ^{2),6)}
^{35}Cl	0.0	0.114	1.00	0.209 ¹⁾
	1.18-4.09	0.419 ⁴⁾		0.014 ^{1),4)}
	≥ 4.6			0.000 ²⁾
total				0.223

¹⁾ Normalized to known mirror β decay rates

²⁾ Shell model estimates [7,8]

³⁾ Determined from γ decay rates (see text)

⁴⁾ Sum of six allowed transitions

⁵⁾ Results multiplied by $^6\text{Li}/^7\text{Li}$ abundance ratio

⁶⁾ Results multiplied by $^{10}\text{B}/^{11}\text{B}$ abundance ratio

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FIGURES

FIG. 1. Number of events, in one MeV bins, for the indicated targets and exposures, after folding with the anticipated resolution of SuperKamiokande. Each grouping of four bars corresponds, from the left to right, to scenarios $i)$ through $iv)$ (see text). The darkened portions indicated the $\pm 1\sigma$ statistical errors. In each case, the last bin shown contains all events of that energy and above.

FIG. 2. The ratio of the solute and ν -e event rates, shown in one MeV bins and normalized in each bin to the results for scenario $i)$. The labelling is as in Fig. 1. In Fig. 2c, only the nonisotropic component of the ^{11}B event rate has been retained.



